

Dwarf galaxy populations in present-day galaxy clusters: II. The history of early-type and late-type dwarfs

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ABSTRACT

How did the dwarf galaxy population of present-day galaxy clusters form and grow over time? We address this question by analysing the history of dark matter subhaloes in the Millennium-II cosmological simulation. A semi-analytic model serves as the link to observations. We argue that a reasonable analogue to early morphological types or red-sequence dwarf galaxies are those subhaloes that experienced strong mass loss, or alternatively those that have spent a long time in massive haloes. This approach reproduces well the observed morphology-distance relation of dwarf galaxies in the Virgo and Coma clusters, and thus provides insight into their history. Over their lifetime, present-day late types have experienced an amount of environmental influence similar to what the progenitors of dwarf ellipticals had already experienced at redshifts above two. Therefore, dwarf ellipticals are more likely to be a result of early and continuous environmental influence in group- and cluster-size haloes, rather than a recent transformation product. The observed morphological sequences of late-type and early-type galaxies have developed in parallel, not consecutively. Consequently, the characteristics of today's late-type galaxies are not necessarily representative for the progenitors of today's dwarf ellipticals. Studies aiming to reproduce the present-day dwarf population thus need to start at early epochs, model the influence of various environments, and also take into account the evolution of the environments themselves.

Key words: galaxies: abundances – galaxies: clusters: general – galaxies: dwarf – galaxies: evolution – galaxies: haloes – galaxies: statistics

1 INTRODUCTION

The filamentary large-scale distribution of galaxies (Gott et al. 2005) implies that any given galaxy cluster is connected to a number of surrounding environments with different characteristics. These connections evolve with time: galaxies and galaxy groups get accreted, contributing to the growth of cluster and supercluster environments (Springel et al. 2005; Klypin et al. 2011). As a consequence of this “cosmic web” and its inhomogeneous density distribution on megaparsec scales, observed galaxy properties at low redshift depend not only on the local environment – their current group or cluster (e.g. Gavazzi et al. 2010) – but also on the surrounding larger environment (Mahajan et al. 2011, 2012; Lietzen et al. 2012).

To investigate the influence of environment on galaxies, dwarf galaxies serve as ideal tracers. Their abundance is large (Trentham & Tully 2002), and their shallow potential (de Blok et al. 2008) makes them susceptible to external processes, namely gravitational forces and ram pressure (Gnedin 2003b;

Mayer et al. 2006). However, observations can merely provide a present-day snapshot of different dwarf galaxy populations that have evolved in parallel, not a sequence of their past evolution. We therefore utilise cosmological simulations and models to gain insight into the history of dwarf galaxy populations within a Λ CDM framework. Our focus lies on present-day massive galaxy clusters, which are the largest and probably best studied environments of the nearby universe beyond the Local Group (see, e.g., Boselli et al. 2011 and Ferrarese et al. 2012).

Observations of dwarf galaxies in nearby clusters have become increasingly refined (Adami et al. 2005; Ferrarese et al. 2006; McDonald et al. 2009; Penny et al. 2009; Hammer et al. 2010; Lieder et al. 2012; Ryś et al. 2012; Smith et al. 2012c), and have been complemented by dedicated simulations and models (Moore et al. 1999; Brüggen & De Lucia 2008; Boselli et al. 2008b; Aguerri & González-García 2009; De Rijcke et al. 2010; Smith et al. 2010; Schroyen et al. 2011; Smith et al. 2012b). However, Λ CDM N-body simulations of cosmological volumes have only recently reached the regime of dwarf galaxies in their mass resolution (Boylan-Kolchin et al. 2009; Klypin et al. 2011). The large dynamic range between a dwarf galaxy and its host cluster

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makes cosmological hydrodynamical simulations of their evolution difficult. A viable alternative is provided by semi-analytic models applied to merger trees of N-body simulations. While such models have contributed to increase our understanding of higher mass galaxies, they have not been exploited much in the study of cluster dwarf galaxies until recently (Peng et al. 2008; De Lucia et al. 2012b), paralleling a larger number of studies for Milky Way sized haloes (e.g. Macciò et al. 2010, Font et al. 2011, and Helmi et al. 2012). The first semi-analytic model based on the Millennium-II simulation (Boylan-Kolchin et al. 2009) was released by Guo et al. (2011). It was tuned to reproduce the redshift-zero stellar mass function down to $\log(M_*/M_\odot) \sim 7.5$ and the luminosity function down to $M_r = -15$ mag. In this series of papers, we use the model of Guo et al. (2011) in combination with observational data for nearby galaxy clusters to investigate the properties of their faint, low-mass galaxy population.

Of particular interest are early-type dwarf galaxies, as they are the dominant galaxy population by number in massive galaxy clusters (Jerjen & Tammann 1997). Their origin is still not fully understood, for several reasons. First, it is still debated whether or not their basic scaling relations are a mere continuation of those of bright early types or are distinct from them (Jerjen & Binggeli 1997; Graham & Guzmán 2003; Côté et al. 2007; Janz & Lisker 2008; Chilingarian 2009; Janz & Lisker 2009; Kormendy et al. 2009; Glass et al. 2011; Graham 2011; Kormendy & Bender 2012). Second, despite their similar overall characteristics in different environments (De Rijcke et al. 2009), an increasing number of studies has shown a pronounced complexity in the structure, internal dynamics, and stellar populations of early-type dwarf galaxies, revising the picture of a simple galaxy population (Binggeli & Cameron 1991; Geha et al. 2003; Michielsen et al. 2008; Tully & Trentham 2008; Lisker et al. 2009; Toloba et al. 2011; Koleva et al. 2011; Paudel et al. 2011; Janz et al. 2012). Third, due to their low luminosity, mostly faint surface brightness, and small size, studies of dwarf galaxy populations are mainly restricted to the nearby universe (or at least to low redshift, Barazza et al. 2009), thus not probing a large range of lookback time. Fourth, it needs to be appreciated that the regime of potential late-type progenitors of early-type dwarfs is also very diverse, ranging from thin late-type spiral galaxies with small or no bulge (e.g. Kautsch et al. 2006), over blue compact dwarf galaxies with starburst activity (e.g. Papaderos et al. 1996), to diffuse irregulars with low-level star formation (e.g. van Zee 2001). All of these types coexist in the luminosity range of about 10^8 to $5 \cdot 10^9 L_\odot$ (e.g. Sandage & Binggeli 1984), which roughly corresponds to an absolute magnitude range of $-15 < M_r < -19$ mag. Fifth, late-type galaxies that we see today are those that have *not* been transformed to early types, and may thus be only partly representative for the actual progenitor population of early types (e.g. Boselli et al. 2008a).

The last point provides one of the main motivations for the current study. A number of environmental transformation processes have been investigated, whose combined effect may lead from rotating, gas-rich, star-forming low-mass galaxies to dynamically hot, gas-poor, quiescent ones (Moore et al. 1996; Mori & Burkert 2000; van Zee et al. 2004a; von der Linden et al. 2010). Yet at which epochs do these have to operate, in order to reproduce the *real* present-day early-type dwarf population? What were the ‘input galaxies’ like at those epochs, and what were the characteristics of the environment they entered? To what extent can a galaxy’s location at present tell us about the strength and duration of the environmental influence it experienced in the past? These questions set

a basic framework – within a Λ CDM universe – for understanding the origin of the dwarf galaxy population that we observe today.

In Weinmann et al. (2011, hereafter Paper I) we found that the dwarf galaxy abundances, velocity dispersions, and number density profiles observed in nearby massive clusters are generally well reproduced in the Millennium-II simulation and the Guo et al. (2011) semi-analytic model. However, the comparatively low number of faint galaxies in the Virgo cluster center, within 300 kpc around the central galaxy M87, is not reproduced in any model cluster. The model may underestimate tidal disruption for faint galaxies, since the dwarf-to-giant ratio – defined in terms of luminosity – is systematically higher in the model than in the observed nearby clusters. We also found indications that the model probably overestimates environmental effects that lead to star formation quenching in galaxy groups.

In the study presented here, we focus on the mass loss and infall history of subhaloes in the massive clusters of the Millennium-II simulation. Semi-analytic model quantities are used mainly for selecting subhalo samples by galaxy magnitude, and for tracking galaxies with tidally stripped subhaloes. As in Paper I and in Guo et al. (2011), we use a WMAP1 cosmology (Spergel et al. 2003) and assume $h = 0.73$ throughout.

The paper is organised as follows. Section 2 characterises the observational galaxy samples. The dark matter simulation and semi-analytic model are described in Section 3. Our analysis is presented in Section 4, including the comparison between simulated subhalo populations and observed galaxy populations. This is followed by a discussion in Section 5 and by our conclusions in Section 6.

2 OBSERVATIONAL SAMPLES

Details of our Virgo, Coma, and Perseus cluster samples are provided in Paper I. Here we briefly describe the sample selection and characteristics. All samples are limited to “dwarf” magnitudes by requiring the r -band absolute magnitude to be $M_r > -19.0$ mag. At the faint end, magnitude completeness limits were chosen to avoid losing galaxies with very low surface brightness. As outlined in Paper I, very compact galaxies may be missed in the Coma and Perseus cluster samples, but are not expected to contribute more than a few percent to the population. All photometric values were corrected for Galactic extinction (Schlegel et al. 1998).

2.1 Virgo Cluster

Our Virgo sample is based on all certain and possible members listed in the Virgo Cluster Catalog (VCC, Binggeli et al. 1985, 1993), with membership updated by one of us (TL) in May 2008 through new velocities given by the NASA/IPAC Extragalactic Database (NED), many of which were provided by the Sloan Digital Sky Survey (SDSS, Adelman-McCarthy et al. 2007). We exclude galaxies that are likely members of the so-called M and W clouds, located at a distance of 32 Mpc (Gavazzi et al. 1999) in the western part of Virgo. Following Gavazzi et al., galaxies in the projected region of these clouds and with a velocity v_{LG} relative to the Local Group larger than 1900 km/s (with $v_{LG} = v_{heliocen.} + 220$ km/s) are assumed to belong to the clouds, and are therefore excluded from our sample. Note that this had not been done in Paper I, but only affects 34 of over 500 objects. Galaxies for which no velocities are available remain in our sample. We use a distance modulus of $m - M = 31.09$ mag (Mei et al.

2007; Blakeslee et al. 2009) for all sample galaxies, corresponding to $d = 16.5$ Mpc. With the adopted WMAP1 cosmology, this leads to a spatial scale of $79 \text{ pc}''$ or 0.286 Mpc° .

Total r -band magnitudes and colours from *ugriz*-bands were measured by Lisker et al. (2007), Janz & Lisker (2009), and Meyer et al. (2013) on SDSS images from data release 5 (Adelman-McCarthy et al. 2007). This included a proper sky subtraction method (described in Lisker et al. 2007) that avoids the serious overestimation of the sky by the SDSS pipeline for nearby galaxies of large apparent size. For a small fraction of the sample, r -magnitudes were obtained by transforming the VCC B -magnitudes (see the appendix of Paper I). The r -band completeness limit was estimated to be $M_r < -15.2$ mag, which we adopt as the limit for our sample selection.

Our final working sample contains 521 galaxies, of which 442 have spectroscopic heliocentric velocities. The sample is nearly complete out to a projected clustercentric distance of 1.5 Mpc from the central galaxy M 87 – comprising 404 galaxies – but includes galaxies up to 3 Mpc.¹

To compute the red galaxy fraction, we split galaxies using the $g - r$ colour cut from Paper I:

$$(g - r)_{\text{cut}} = 0.4 - 0.03 \cdot (13 + M_r) \quad (1)$$

This cut was chosen blueward of the bulk of galaxies that populate the red sequence.

2.2 Coma Cluster

Our Coma cluster sample is based on the SDSS data release 7 (Abazajian et al. 2009). Total r -band magnitudes and *ugriz*-colours are extracted from the SDSS as Petrosian magnitudes. For all galaxies we use a distance modulus of $m - M = 35.00$ mag (Carter et al. 2008), corresponding to $d = 100.0$ Mpc. We initially include all galaxies with $-19.0 < M_r < -16.7$ mag (see Paper I) and out to a projected distance of 4.2 Mpc from the cluster center, which is defined as midway between the two massive central ellipticals NGC 4874 and NGC 4889.

Objects for which SDSS redshifts are available with a redshift confidence of 95% or higher are considered as members if they lie in the range $4000 \leq cz \leq 10\,000$ km/s. The SDSS spectroscopic coverage reaches only to $M_r \lesssim -17.3$ mag. Those potential member galaxies for which the SDSS does not provide spectroscopic redshifts of acceptable quality were visually inspected to exclude contaminants (stars, parts of galaxies, and objects artificially brightened by a star's halo or a bright galaxy). The total number of objects is 1662, with 481 of them having reliable spectroscopic redshifts.

We then correct the sample statistically for the number of contaminating background galaxies. This is based on a radial number density profile (Appendix A3 of Paper I), which we inspect visually to adopt the value where the profile flattens out as our background value. We verify that this approach works reasonably well by comparing our selection to the galaxy catalogue of Michard & Andreon (2008) for the Coma cluster center (see Paper I for a discussion).

To estimate the red galaxy fraction, which will be used in Section 4.3, we first apply a k -correction (Chilingarian et al. 2010)

¹ In Paper I, we mistakenly stated that a restriction to < 1.5 Mpc would exclude the M49 subcluster, while most of it is actually included (Binggeli et al. 1987). However, none of the results from Paper I would have changed significantly if this subcluster would have been excluded.

to the $g - r$ colours of all galaxies, assuming their redshift is $z = 0.023$. The median k -correction is 0.036 mag. Then we background-correct red galaxies as described above, using the colour cut of eq. 1.

2.3 Perseus Cluster

Our Perseus sample is constructed in a similar way as the Coma sample, based on the SDSS data release 7 and using a statistical correction for background galaxies. SDSS spectroscopic redshifts are not available in this region. We use a distance modulus of $m - M = 34.29$ mag for all galaxies, corresponding to a "Hubble flow distance" of $d = 72.3$ Mpc that is given by NED based on the heliocentric velocity of 5366 km/s from Struble & Rood (1999).

We initially include all galaxies with $-19.0 < M_r < -16.7$ mag and out to a projected distance of 3.8 Mpc from the central galaxy NGC 1275. However, the SDSS coverage of the Perseus cluster outskirts is not complete. The incompleteness remains moderate out to 2.5 Mpc and is corrected for each galaxy by a factor that takes into account the missing area at its clustercentric distance. This area is calculated for each galaxy's position as the part of an annulus around the cluster center that is not included in the roughly rectangular coverage of SDSS data.

As for the Coma sample, all objects were visually inspected to exclude stars, artifacts, and parts of galaxies. The total number of galaxies in the sample is 1607. These are then corrected statistically for the background level revealed by a radial number density profile (Appendix A4 of Paper I). While this level cannot be accurately determined and may influence the number counts in the cluster outskirts, its uncertainty is of minor relevance for the dense inner regions of the cluster.

As for the Coma galaxies, we first apply a k -correction to the $g - r$ colour before background-correcting red galaxies. With the adopted redshift of $z = 0.017$, the median k -correction is 0.029 mag (Chilingarian et al. 2010).

3 DARK MATTER SIMULATION AND GALAXY MODEL

3.1 Overview

Semi-analytic models describe galaxy formation and evolution on the basis of simple analytic recipes that are applied to dark matter merger trees (Kauffmann et al. 1993; Cole et al. 2000; Bower et al. 2006). In our study we use the semi-analytic model of Guo et al. (2011), which was applied to the merger trees of the Millennium-II cosmological simulation (Boylan-Kolchin et al. 2009). The latter simulates the evolution of the dark matter distribution within a periodic box of 137 Mpc side length and a particle mass of $9.45 \times 10^6 M_\odot$.

The Guo et al. (2011) model is based on the model of De Lucia & Blaizot (2007), but contains several modifications. The supernova feedback efficiency for low-mass galaxies was increased considerably, in order to fit the stellar mass function of galaxies at the low-mass end. Furthermore, the prescriptions for calculating the sizes of galaxies and environmental effects were modified (see Paper I for details). In addition, the AGN feedback efficiency was increased.

Friend-of-Friend (FoF) haloes were defined in the Millennium-II simulation by linking particles with separation below 0.2 of the mean value (Davis et al. 1985). Within these FoF haloes, the SUBFIND algorithm (Springel et al. 2001) identified subhaloes, to

which the semi-analytic model associated galaxies. Once the subhalo mass falls below the mass of the galaxy, the model employs an analytic prescription for the galaxy’s orbit (see Guo et al. 2011).

The galaxies and galaxy clusters whose dark matter haloes were simulated by Boylan-Kolchin et al. (2009) and whose baryonic configuration was modeled by Guo et al. (2011) will be referred to as “model galaxies” and “model clusters” throughout the paper. Their properties are publicly provided by the Virgo-Millennium Database (Lemson & The Virgo Consortium 2006).² While we primarily make use of properties provided by the dark matter simulation itself (such as position and mass of a subhalo), we rely on the semi-analytic model for selecting galaxies by their r -band magnitude, their stellar mass, and for tracking so-called orphan galaxies, which have already lost their dark matter subhalo. Magnitudes of model galaxies are based on the stellar evolutionary synthesis models of Bruzual & Charlot (2003), which were found by Hansson et al. (2012) to well reproduce the *ugriz*-colors of galaxies in the nearby universe. Since there are indications that the semi-analytic model does not correctly reproduce dust attenuation (Paper I; Weinmann et al. 2012), we chose to use dust-free magnitudes.

3.2 Selection of model clusters and their galaxies

For comparing the model galaxies and clusters to observations, we define three samples of model clusters. The full sample comprises the 15 most massive galaxy clusters at redshift zero³ of the Millennium-II simulation. The “SAM-V” sample only uses the twelve least massive clusters of the full sample, thereby covering the published range of virial masses of the Virgo cluster ($1.4 - 4.0 \times 10^{14} M_{\odot}$, based on Böhringer et al. 1994, McLaughlin 1999, Schindler et al. 1999, Urban et al. 2011, and Paper I). The “SAM-CP” sample only uses the three most massive clusters of the full sample, with 4.5×10^{14} , 4.7×10^{14} , and $9.3 \times 10^{14} M_{\odot}$. These cover the range of published Perseus cluster masses (Eyles et al. 1991; Simionescu et al. 2011; Paper I), and reach at least close to the Coma cluster mass of $1.3 \times 10^{15} M_{\odot}$ (Łokas & Mamon 2003). When using observer-like quantities in our analysis, we consider each cluster from three different sightlines, namely along the x , y , and z axis of the simulation box. Unless noted, our analysis relies on the full cluster sample.

A model galaxy is included in our samples if it lies within a three-dimensional clustercentric distance of $3 \text{ Mpc}/h$. The cluster center is defined as the location of the central galaxy in the FoF halo, placed at the potential minimum of the FoF halo by the semi-analytic model. For the full and the SAM-V samples, we restrict model galaxies to a magnitude range of $-19.0 < M_r < -15.2 \text{ mag}$. For the SAM-CP sample, the magnitude range is $-19.0 < M_r < -16.7 \text{ mag}$.

Some galaxies that lie beyond $3 \text{ Mpc}/h$ from the center may nevertheless be seen at a much lower *projected* clustercentric distance. We test for such “interlopers” in the SAM-V clusters by extracting all model galaxies with velocities in the range $\pm 1800 \text{ km/s}$ around the respective central cluster galaxy.⁴ For the model clus-

ters, we adopt a distance of 16.5 Mpc from a virtual observer – corresponding to the Virgo value – and select only galaxies with line-of-sight distances up to a factor of 1.5 larger or smaller. The fainter or brighter absolute magnitudes that an observer would erroneously derive when assuming them to be cluster members are taken into account for the selection. We expect that distinct structures outside of this distance range, like the Virgo clouds mentioned in Section 2.1, could be identified by observers and would thus not be counted as cluster members in observational samples.

At any projected clustercentric distance below 0.5 Mpc , the fraction of interlopers is 1% or less. For sightlines parallel to the x and y axis of the simulation box, the interloper fraction remains below 5% out to 1.5 Mpc , which is the completeness limit of the Virgo cluster sample. For sightlines parallel to the z -axis, this fraction remains below 10%. Between 1.5 and 2 Mpc , the interloper fraction does not exceed 10% for all sightlines. Therefore, our neglect of interlopers will not make a difference for the comparison of model clusters to the Virgo cluster. For the Coma and Perseus clusters, which we consider up to 3 Mpc , the rising interloper fraction (reaching values of 30% and more) may seem relevant. On the other hand, we do correct the observed samples statistically for background galaxies, to which interlopers would be counted. Notwithstanding the uncertainty on the adopted background level (see Paper I) and possible effects of cosmic variance, the fact that the correction is done separately for red and for all galaxies reduces a potential effect of interlopers on the colour-distance relation, which is subject of our analysis in Sect. 4.4.

Finally, we remark that the stellar bulge-to-total mass ratio of our model galaxies is 0.03 or less for 50% of objects and 0.10 or less for 75% of objects. Only 10% of model galaxies are bulge-dominated, i.e. have a bulge-to-total ratio of 0.5 or larger. This seems consistent with the observational result that the vast majority⁵ of these galaxies do not possess structural components with surface brightness profiles steeper than a Sérsic index of 2 (Graham & Worley 2008; Janz et al. 2013).

4 ANALYSIS

The presence of significant tidal forces is a natural characteristic of Λ CDM cluster and group environments, both due to the overall potential and to close encounters of subhaloes. The interplay of mass and gravitation cannot be avoided by the member galaxies, and causes significant mass loss of their subhaloes. However, we need to ask whether the stellar and gaseous components of a galaxy are necessarily affected when its subhalo loses mass. The link between dark matter and baryons is provided by dedicated simulations of individual galaxies moving within the gravitational potential of a galaxy cluster and experiencing encounters with other subhaloes (Moore et al. 1998; Gnedin 2003b; Mastropietro et al. 2005; Smith et al. 2010). While depending on the specific trajectories and also on the local structure of the gravitational potential (Gnedin 2003a), the strongest effects on the baryonic configuration appear

² <http://gavo.mpa-garching.mpg.de/MyMillennium/>

³ This corresponds to the last snapshot of the simulation. In Paper I we used the second-to-last snapshot, at a lookback time of 263 Myr and a redshift of $z = 0.020$, which is closer to the redshift of the Coma and Perseus clusters.

⁴ This range is larger than two times the line-of-sight velocity dispersion of each model cluster sightline, except for one sightline to one cluster (Paper I).

⁵ Note that our term “dwarf galaxies” refers to a simple magnitude selection of $-19.0 < M_r < -15.2 \text{ mag}$, not to any selection in surface brightness. Observational samples of early-type galaxies in this range do include a small fraction of objects classified as “low-luminosity elliptical/S0” galaxies (Janz & Lisker 2008), which differ from the more diffuse “dwarf elliptical/S0” galaxies. Having a small number of bulge-dominated galaxies in the sample thus seems reasonable from an observational point of view.

in cases with the strongest dark matter mass loss. We can thus assume that, statistically, the more dark matter was lost by a given subhalo over time, the more its stellar structure was tidally heated, leading to thickening or even destruction of disks and causing mild to strong stellar mass loss (Mastropietro et al. 2005; Smith et al. 2010). In the course of our analysis, we will therefore focus on the mass loss experienced by the subhaloes in the Millennium-II simulation. However, since mass loss itself does not directly indicate in which environment a galaxy resided, we additionally consider the total time that it has spent in massive haloes. This allows us to examine whether subhaloes that have suffered stronger mass loss have necessarily resided longer in high-mass environments.

4.1 Infall time and mass loss

In the upper panel of Fig. 1 we show the distribution of lookback times to when the model galaxies became a satellite for the first time, when they entered a halo with mass $M \geq 10^{12} M_\odot/h$, a halo with mass $M \geq 10^{13} M_\odot/h$, and when they entered the cluster halo of which they are a member today. Since the simulation output is provided in discrete snapshots, we work with the simulation snapshot *immediately before* a galaxy appeared as member of the respective FoF halo for the first time.

Almost 1600 galaxies (17.2%) are not yet a member of the cluster – in the sense of belonging to its FoF halo – but are located within 3 Mpc/h of the cluster center. These objects are assigned a lookback time of zero. They are not included in the similar distributions of infall time presented by De Lucia et al. (2012b, their Fig. 7), which are otherwise consistent with our distributions.⁶

While the distributions shown in Fig. 1 are a combination of 15 clusters, a significant scatter between individual clusters exists, depending on which lookback time is chosen. The average lookback time to when 50% of today's dwarf galaxies had entered their cluster halo is 5.55 Gyr, with a rather large standard deviation of 1.51 Gyr. This is mainly due to major merger events of the cluster haloes themselves, during which large groups or clusters are being accreted. These events thus set the cluster infall time for a significant fraction of today's galaxies. If we focus instead on the infall time into a halo with mass $M \geq 10^{13} M_\odot/h$ – no matter whether or not it was the progenitor of today's cluster halo – the scatter is much smaller: the average lookback time is 7.33 Gyr with a standard deviation of only 0.55 Gyr between the clusters. For the infall time into a halo with mass $M \geq 10^{12} M_\odot/h$, the value is 8.72 ± 0.45 Gyr.

When choosing as reference the subhalo mass immediately before it became a satellite for the first time, a relative mass loss can be defined and compared for the different lookback times (lower panel of Fig. 1). Objects that have never been a satellite before the respective point of time are assigned a mass loss value of zero. This is why the peak in the figure at a value of zero increases with larger lookback time. Subhaloes that grew in mass since they first became a satellite appear with negative mass loss values in the figure, as indicated there.

For a significant fraction of objects, a major part of the subhalo mass had been lost already before entering today's cluster halo and even before entering a halo with $10^{13} M_\odot/h$. Only when looking back to the infall into a halo with $10^{12} M_\odot/h$, the fraction of

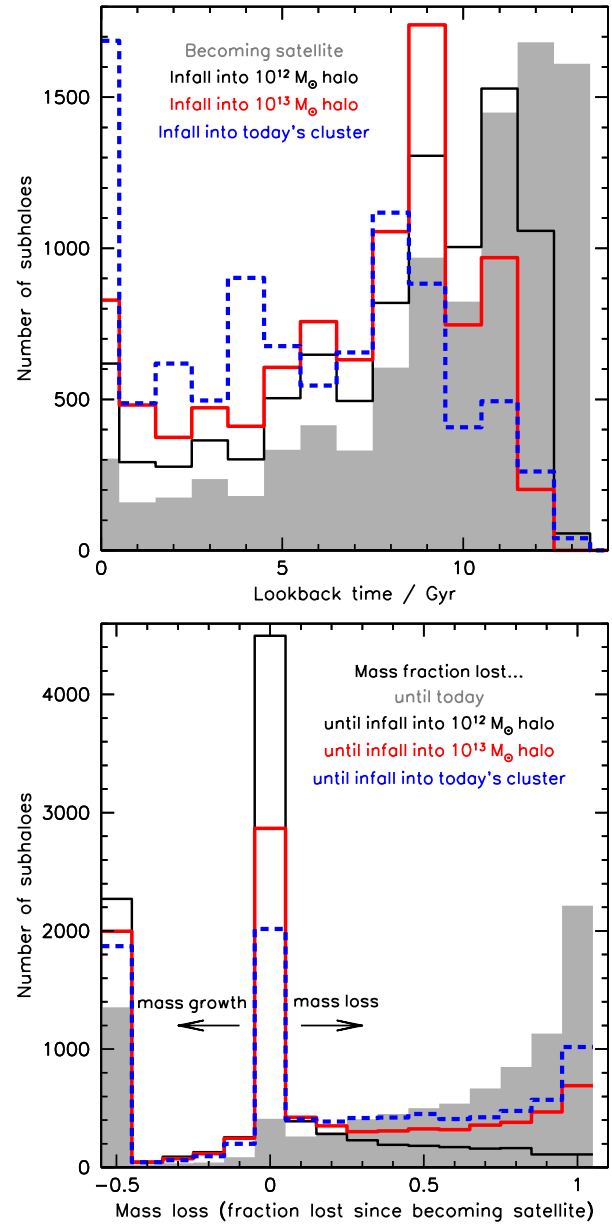


Figure 1. *Top:* For the dwarf galaxies in the 15 most massive clusters of the Millennium-II simulation, we compare the lookback time to when a subhalo first became a satellite, when it entered a halo with mass $M \geq 10^{12} M_\odot/h$, a halo with mass $M \geq 10^{13} M_\odot/h$, and today's cluster halo. *Bottom:* Here we compare the subhalo mass loss, relative to when it first became a satellite, for four different times: today ($z = 0$), when it first entered a halo with mass $M \geq 10^{12} M_\odot/h$, a halo with mass $M \geq 10^{13} M_\odot/h$, and today's cluster halo. If one of these times is the same as the first time of becoming a satellite, the mass loss is set to zero. Negative mass loss values mean that the mass has increased since becoming a satellite. We assign orphan galaxies a subhalo mass corresponding to 19 particles, i.e. one particle below the resolution limit.

objects that had already lost the majority of their mass *before* this event drops below 10% (black histogram in Fig. 1, lower panel). At that point of time, most subhaloes either experienced their first time of becoming a satellite – thus having a mass loss value of zero – or had even grown in mass since becoming a satellite. The latter is possible because many objects became first-time satellites at very early epochs (see the upper panel of the figure), when they were still

⁶ Note that Guo et al. (2011) and De Lucia et al. (2012b) use the *most recent* time when a galaxy has become a satellite, whereas we use the *first* time when it became a satellite.

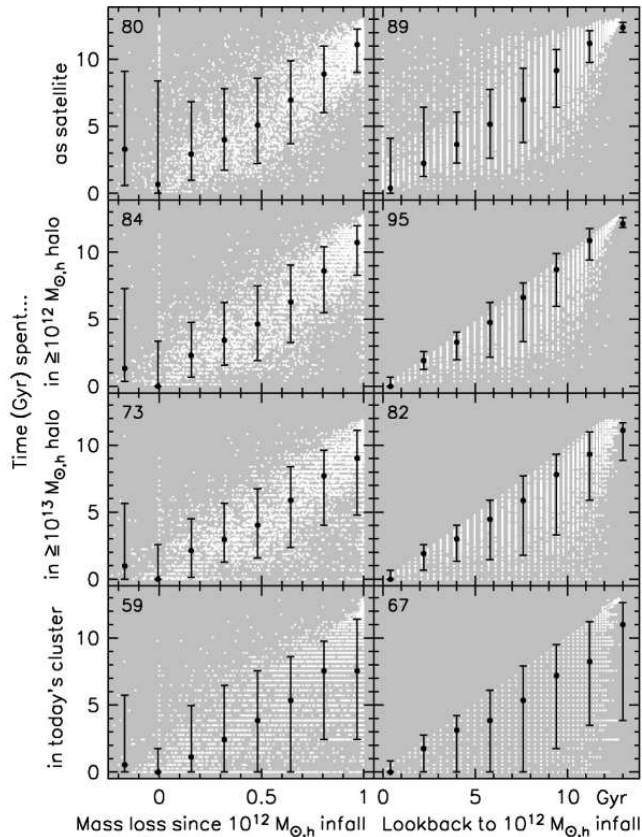


Figure 2. For the dwarf galaxies (white dots) in the 15 most massive clusters of the Millennium-II simulation, we show on the abscissa the lookback time to when a subhalo first entered a halo equal to or more massive than $10^{12} M_{\odot}/h$ (right panels) and the subhalo mass loss since that time (left panels). On the ordinate, we show from top to bottom the time spent as satellite, the time spent in haloes with mass $M \geq 10^{12} M_{\odot}/h$, with $M \geq 10^{13} M_{\odot}/h$, and the time spent in today’s cluster halo. Black circles and error bars denote the median and the $\pm 40\%$ range in eight evenly spaced intervals. The black number in the top of each panel is the Spearman’s rank correlation coefficient multiplied by 100, calculated within the panel limits.

very small in mass, and shortly afterwards they became again “centrals”, i.e. the most massive galaxies of their respective haloes. This allowed them to continue growing significantly. Choosing as reference the first time of becoming a satellite thus seems only moderately useful. Instead, our reference from now on will be the time when first entering a halo with mass $M \geq 10^{12} M_{\odot}/h$ (also see McGee et al. 2009). Only 2.2% of subhaloes possess a larger mass today than at this point of time, while the fraction is 17.3% when comparing to the mass at becoming a satellite.

Since subhalo mass loss is caused by the tidal forces acting on a galaxy, we expect it to be a more direct proxy for the environmental influence – also on the baryonic part – than the lookback time to infall into a halo of a certain mass. Furthermore, the total time spent in massive haloes should also be somewhat closer related to environmental influence than the lookback time to the infall event. In contrast to the mass loss, which depends on the orbit and the occurrence of encounters, the time spent in massive haloes can tell whether the progenitors of different galaxy populations have evolved in *different environments*, thus providing complementary information.

The three quantities are compared to each other in Fig. 2.

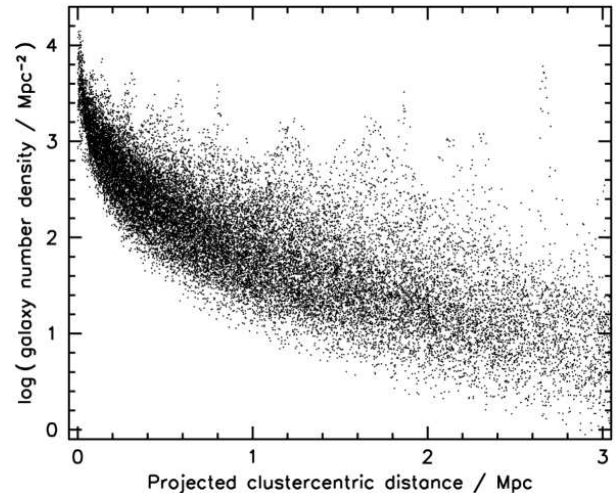


Figure 3. For the dwarf galaxies in the 15 most massive clusters of the Millennium-II simulation, we show the projected clustercentric distance versus the logarithm of the local projected galaxy number density. The latter is derived following Dressler (1980), by using the minimum radius of a circle that encompasses – in projection – the tenth nearest neighbour galaxy, counting all galaxies with $M_r < -15.2$ mag. The density is then calculated as 11 divided by the area of that circle in Mpc^2 .

They obviously follow clear correlations, but also show significant scatter. For example, the time spent in haloes with mass $M \geq 10^{12} M_{\odot}/h$ can be much shorter than the lookback time to the first infall into such a halo (right panel in second row from top), indicating that galaxies can pass through and escape a massive halo. Those (few) subhaloes that have grown in mass since their infall into a $10^{12} M_{\odot}/h$ halo can have spent very different amounts of time in such haloes, from almost zero to more than 7 Gyr (left panel in second row from top). Moreover, we emphasize that the scatter of the time spent in today’s cluster halo is large (bottom panels): for many galaxies, this time just means the most recent stage of their evolution, not necessarily being representative of what they experienced before.

4.2 Present-day location versus environmental influence

The quantities of the subhalo population that are most directly accessible to an observer are the projected position and line-of-sight motion. We will address the line-of-sight velocity in Section 4.6, but focus here on location, i.e. projected distance from the respective cluster center. In addition, we also consider the commonly used quantity local density, i.e. the projected number density of galaxies calculated from the area encompassing the 10th neighbour (Dressler 1980). Both are compared in Fig. 3, showing a clear correlation, but with significant scatter. Part of the scatter is due to cluster substructure: a subclump with relatively high local density may be located comparatively far away from the cluster center. This is the case, for example, with the Virgo cluster and its M 49 subcluster, which is more than 1 Mpc away in projection from the central Virgo galaxy M 87.

In Fig. 4 we show how both clustercentric distance and local density correlate with subhalo history, i.e. with lookback time to infall, time spent in haloes with $M \geq 10^{12} M_{\odot}/h$, and mass loss. All correlations are similarly strong for clustercentric distance as for the logarithm of local density, judging from the visual impression as well as from the correlation coefficient given in each figure

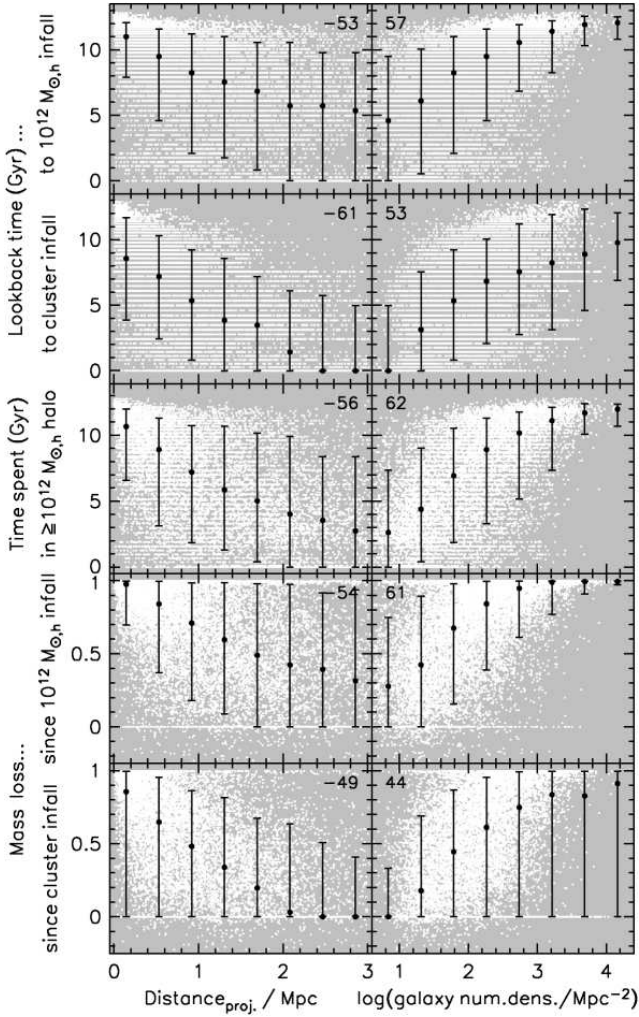


Figure 4. For the dwarf galaxies (white dots) in the 15 most massive clusters of the Millennium-II simulation, we show on the abscissa the projected clustercentric distance (left panels) and the logarithm of the local projected galaxy number density (right panels). On the ordinate, we show from top to bottom the lookback time to when a subhalo first entered a halo with mass $M \geq 10^{12} M_{\odot}/h$, the lookback time to when it entered today's cluster halo, the time spent in haloes with mass $M \geq 10^{12} M_{\odot}/h$, the subhalo mass loss since it first entered a halo with mass $M \geq 10^{12} M_{\odot}/h$, and the mass loss since it entered today's cluster halo. Black circles and error bars denote the median and the $\pm 40\%$ range in eight evenly spaced intervals. The black number in the top of each panel is the Spearman's rank correlation coefficient multiplied by 100, calculated within the panel limits.

panel. Objects located at small clustercentric distances, and likewise in regions of high local density, experienced on average early infall, have spent a long time in massive haloes, and have suffered strong mass loss. However, the scatter is large, clearly illustrating that the past environmental influence can not simply be read off from the (projected!) clustercentric distance today. There is more than 50% overlap between the subhaloes at less than 0.5 Mpc from the cluster center and those between 1 and 2 Mpc in terms of the time spent in haloes with $M \geq 10^{12} M_{\odot}/h$, the mass loss experienced in such haloes, and also the lookback time to infall into today's cluster. Only part of this overlap is caused by projection effects — even when considering three-dimensional clustercentric distance, the statement still holds. We conclude that the subhalo populations in the cluster center and the outer cluster regions do

show systematic differences in their histories *on average*, but that two subhaloes located at the same clustercentric distance or local density today may have experienced strongly different environmental influence in the past. Two subhaloes located at very different clustercentric distances or local densities may have had similar histories (cf. Gnedin 2003a; De Lucia et al. 2012b). In the following section, we will attempt to map these subhalo properties to the observed galaxy population.

To ensure that our selection of model galaxies in r -band magnitude instead of stellar mass does not introduce a bias, we examine the above relations with clustercentric distance for model galaxies in the following stellar mass intervals: $0.1 - 0.4 \times 10^8 M_{\odot}$, $0.4 - 2.0 \times 10^8 M_{\odot}$, $2 - 10 \times 10^8 M_{\odot}$, $10^9 - 10^{10} M_{\odot}$, and $10^{10} - 10^{12} M_{\odot}$. We find that the radial trends, as well as the scatter of values, are remarkably similar in all but the most massive interval. For the lookback time to entering a halo with $M \geq 10^{12} M_{\odot}/h$, the mass loss since then, and the time spent in such haloes, the median values differ by less than 10% at projected clustercentric distances below 1 Mpc and less than 20% out to 3 Mpc. The most massive interval differs by less than 20% below 1 Mpc and up to 70% out to 3 Mpc. The $\pm 40\%$ ranges differ by less than 20% except for the mass loss below 1 Mpc, where the range can be different by a factor of two. In the most massive interval outside of 1 Mpc, the $\pm 40\%$ range of mass loss already includes objects that have grown in mass (i.e. with negative mass loss values), thereby increasing the range significantly. However, for low-mass galaxies, this test confirms that our analysis is not biased by our specific magnitude selection of model galaxies, which is tied to the observational samples.

4.3 Morphology-distance relation

We now assume that, for dwarf galaxies, stronger environmental influence in the past led to early-type morphology today. The present-day late-type galaxies would therefore be those on which environment had the weakest effect. We thus attempt to assign subhalo populations with different mass loss histories to the observed populations of galaxies with different morphology. The latter are taken from the Virgo cluster and are subdivided into three classes: (i) elliptical and dwarf elliptical galaxies without disk features or blue central regions; (ii) lenticular galaxies, Sa-type spirals, dwarf ellipticals that exhibit disk features and blue central regions, and transition types between dwarf elliptical and irregular galaxies; (iii) all remaining spiral galaxies, as well as irregular and blue-compact dwarf galaxies. When considering only Virgo galaxies up to a projected distance of 1.5 Mpc from M 87 (which we assume to be the cluster center), these classes comprise 50.1%, 21.9%, and 27.9% of galaxies, respectively. Their distribution with clustercentric distance is shown in the top panel of Fig. 5, reflecting the well-known morphology-density relation (Dressler 1980).

The above percentages are now used to subdivide the model galaxies by their subhalo mass loss, and alternatively by the time spent in haloes with $M \geq 10^{12} M_{\odot}/h$, assuming these quantities represent the strength of environmental influence. The resulting distributions with clustercentric distance are shown in the two middle panels of Fig. 5. They look similar to the observed relation of galaxy morphologies, but have a larger contrast between the inner and outer populations. Subhaloes that experienced strong mass loss or spent a long time in massive haloes dominate in the center, but already beyond 0.75 Mpc they are outnumbered by those with weak mass loss or a short time spent in massive haloes. In contrast, the

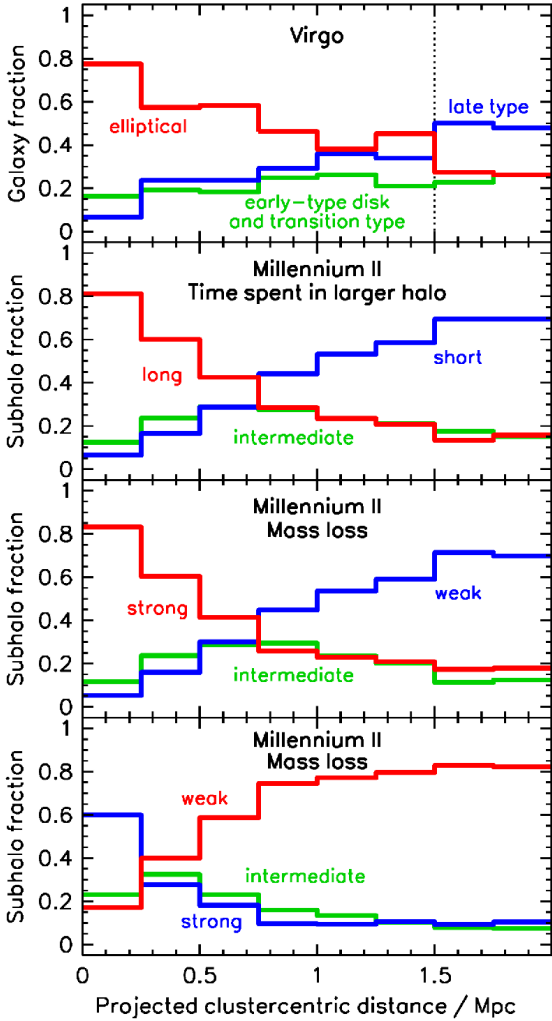


Figure 5. Clustercentric distribution of galaxies and subhaloes. The top panel shows the Virgo cluster morphological types. These type percentages – using only galaxies up to 1.5 Mpc projected distance – are then used to subdivide the subhalo population accordingly. The second and third panel from top show the resulting distributions when subdividing by the time spent in massive haloes, or by the mass loss. For the lower panel, we assume the opposite mapping of observed and model galaxies, to illustrate that this would lead to a discrepant distribution. We use the SAM-V sample of model clusters for this figure (see Section 3).

elliptical galaxies in the Virgo cluster dominate over the late types out to 1.5 Mpc.

The above assignment of percentages assumes that strong mass loss correlates with early-type morphology. When we assume instead the opposite, namely that late-type galaxies are those that experienced the strongest mass loss, the lower panel of Fig. 5 shows the resulting relation with clustercentric distance. This scenario would lead to a relation that is opposite to the observed morphology-distance relation, with a strongly increasing elliptical fraction towards the cluster outskirts. This illustrates that our above assumption was reasonable, and that one cannot simply assume any arbitrary correlation between dark matter mass loss and baryonic morphology. If we assumed that no correlation exists, this would lead to a scenario in which any given galaxy type would have to cover the full range of mass loss values. For example, the population of late-type, star-forming galaxies would have to be com-

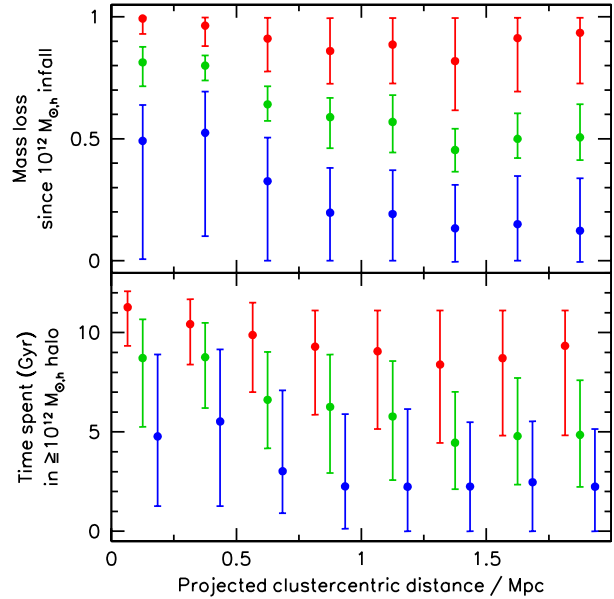


Figure 6. Similar to Fig. 5, but now using the morphological percentages of each individual radial bin of the Virgo cluster distribution to subdivide the model galaxy population of that bin by mass loss (top panel). Points and error bars denote the median and the $\pm 40\%$ range. The bottom panel shows the resulting distribution of the time spent in haloes with $\geq 10^{12} M_{\odot}/h$. We use the SAM-V sample of model clusters for this figure (see Section 3).

posed partly of galaxies whose subhaloes have lost almost all of their mass, but also of galaxies whose subhaloes have experienced almost no mass loss. All of these would intriguingly have to show a very similar appearance today, since all belong to the same galaxy type. This appears rather unlikely, given that N-body simulations of tidal forces in galaxy clusters show that objects losing a major fraction of their dark matter *are* affected in their stellar configuration as well (Gnedin 2003a; Mastropietro et al. 2005).

When we subdivide the model galaxies of the SAM-V sample by their subhalo mass loss as outlined above, the median $g-r$ colour of the early-type analogues turns out to be 0.70, which is slightly redder than the intermediate-type analogues (0.66) and clearly redder than the late-type analogues (0.55). This is a consequence of the implementation of environmental effects in the semi-analytic model (see Paper I and Guo et al. 2011 for details): objects with stronger mass loss have become satellites of massive haloes at earlier times (Fig. 2). While it lends support to our approach, it needs to be remarked that model colours are too red as compared to observations (see the analysis and discussion in Paper I). The Virgo cluster early-type dwarfs have a median $g-r$ colour of 0.60, the intermediate types have 0.60 as well, and the late types have 0.39.

Instead of using only one set of population percentages, derived from all galaxies up to 1.5 Mpc from the center, we can map model galaxies to observed ones for each clustercentric distance bin individually. This is shown in the top panel of Fig. 6, using mass loss to subdivide the populations. As a result, we can see that there exists a relation of mass loss and distance *within* each class of galaxies. This is a direct consequence of the fact that the relation with distance in Fig. 5 is steeper for model galaxies than for observed ones when using a *fixed* value to separate galaxy populations: the decline *within* the populations was not taken into account. It is most pronounced for the late-type analogues, which reach a

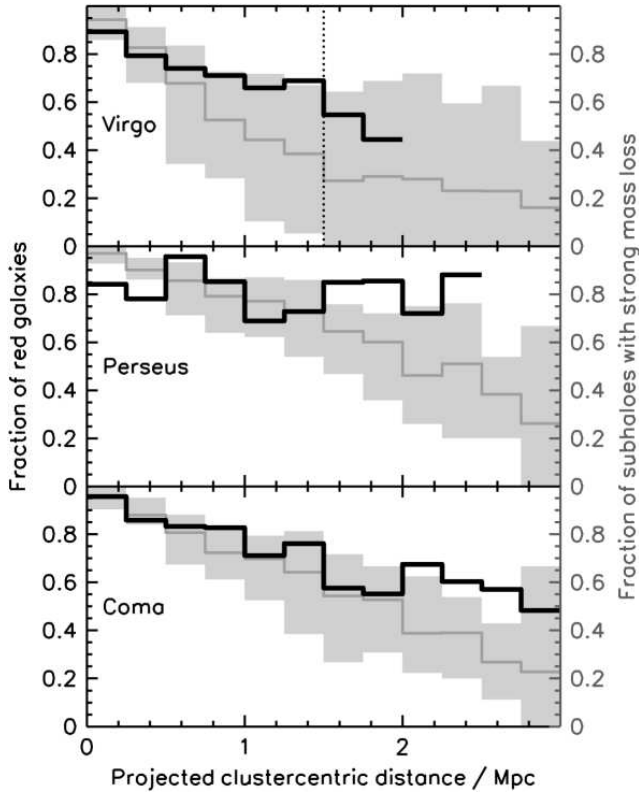


Figure 7. Red dwarf galaxy fractions (black line) and subhalo fractions with strong mass loss (grey line and shaded area) are shown with respect to projected clustercentric distance for observed clusters (Virgo, Perseus, Coma) and their corresponding model cluster samples (SAM-V for Virgo, SAM-CP for Coma and Perseus, see Section 3). Red galaxies are defined according to eq. 1, following Paper I. The shaded areas indicate the minimum-to-maximum range of the different model clusters and their different projections. Subhaloes with strong mass loss are selected similar to Fig. 5: we apply the percentage of red galaxies inside a projected distance of 1.5 Mpc (Virgo) and 2.0 Mpc (Perseus and Coma) to the model samples. The Virgo sample becomes incomplete beyond 1.5 Mpc, indicated by the vertical dotted line. The Perseus sample is statistically corrected for incomplete coverage (Sect. 2.3), but this becomes unreliable beyond 2.5 Mpc due to too small coverage.

median mass loss value of 50% in the inner cluster regions, but drop to less than 15% in the outskirts. This could indicate a mass loss threshold for the onset of noticeable effects on the stellar configuration. Without a major loss ($\gtrsim 50\%$) of subhalo mass, galaxies were able to keep their late-type appearance.

In addition to mass loss, we show in the bottom panel of Fig. 6 the time spent in massive haloes that results from the above subdivision by mass loss. Again, there is a significant trend within each class, especially for intermediate- and late-type galaxies. Intermediate-type galaxies in the innermost radial bin have spent a similar time in massive haloes as elliptical galaxies located in the outskirts. The same is true for late-type galaxies in the innermost radial bin as compared to intermediate-type ones in the outskirts.

However, we have so far considered the combination of all model clusters of the SAM-V sample, and all their projections. If the Virgo cluster is not a typical cluster, the actual distribution of mass loss with clustercentric distance may be different than shown in Fig. 6. We have inspected the individual projections of the twelve SAM-V clusters, and found that in a few of the 36 cases, the relation within a given subclass almost disappears. Moreover, the stellar and

gas structure of a galaxy may be governed by further parameters in addition to subhalo mass loss, which could help understanding why late-type galaxies in the center have mass loss values similar to intermediate-type galaxies in the outskirts. These aspects illustrate how complex it is to interpret the observed galaxy populations correctly.

4.4 Colour-distance relation

A similarly complete galaxy catalog as for the Virgo cluster does not exist for the Coma and Perseus clusters (only for the Coma center, see Michard & Andreon 2008), but an analogous comparison between observed and model galaxies can be done based on galaxy colour, as shown in Fig. 7. While colour is not a direct proxy for morphology, galaxies in most clusters show a colour-distance relation similar to the morphology-distance relation. This can be seen in the top and bottom panels of the figure: the red galaxy fraction of the Virgo and Coma cluster declines with increasing distance (black line). Red galaxies are selected by eq. 1 after applying a k-correction to Coma and Perseus galaxies (Sects. 2.2 and 2.3). Interestingly, the red galaxy fraction of the Perseus cluster does not decrease at all when going outwards. This shows that significant scatter exists among the properties of present-day massive galaxy clusters (also see Paper I), and an individual cluster can not necessarily be taken as representative of the majority of clusters.

To obtain distributions of subhaloes with strong mass loss, we apply for each observed cluster the overall percentage of red galaxies to its corresponding model cluster sample, analogous to Fig. 5. The resulting subhalo distributions are shown with grey lines, and the shaded area indicates the full range of distributions that occur among the various projections of the different model clusters. For the Virgo cluster, a similar trend is seen as for morphology: the fraction of subhaloes with strong mass loss decreases more strongly than the observed fraction of red galaxies. Nevertheless, the Virgo cluster still lies within the range of the different model cluster projections, same as the Coma cluster in most radial bins. The Perseus cluster with its flat observed distribution falls outside of the model cluster range in half of the radial bins. However, it needs to be emphasized that the SAM-CP sample consists only of the three most massive model clusters. With a larger model sample – requiring a cosmological simulation with larger box size at the Millennium-II resolution – the range of distributions may become larger.

4.5 Mass loss history of galaxy populations

To what extent is the present-day population of late-type galaxies in clusters comparable to the *former* progenitors of today’s early types? We address this question by comparing the mass loss distributions of these populations with each other, assuming that subhalo mass loss serves as a proxy of the environmental influence on the (baryonic) galaxy. Following the subdivision of Virgo cluster galaxy types described in Section 4.3, we select subhaloes representing elliptical, intermediate, and late-type galaxies in the model clusters, and show their mass loss distributions in Fig. 8. In the top panel of the figure, we subdivide the three galaxy types based on the time spent in haloes with $\geq 10^{12} M_{\odot}/h$, while in the bottom panel we subdivide them based on the mass loss itself. As before, mass loss is calculated relative to the subhalo mass immediately before entering a halo with $M \geq 10^{12} M_{\odot}/h$ for the first time.

The mass loss distribution of the present-day late-type galaxies is illustrated by the grey-shaded histogram in the figure. A significant number of objects – note the logarithmic ordinate – have

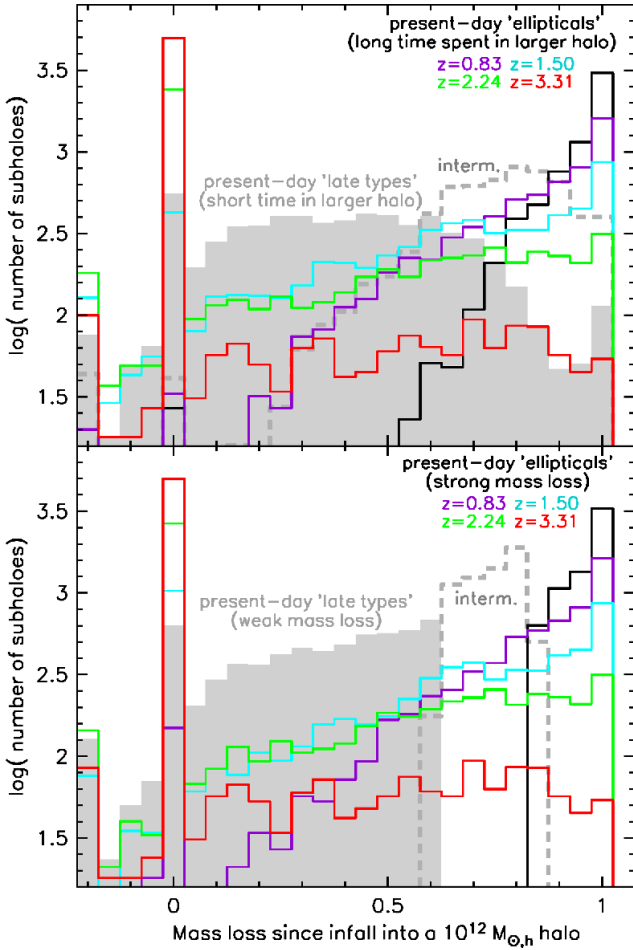


Figure 8. Shown are the distributions of mass loss since entering a halo with $\geq 10^{12} M_{\odot}/h$ for the model galaxy populations defined as in Fig. 5. As in that figure, the model populations ('elliptical', 'intermediate', and 'late-type') can be defined either based on the time spent in massive haloes (top panel) or on the mass loss they experienced (bottom panel). For the 'elliptical' model galaxies only, we show how the mass loss distribution evolves with redshift (coloured lines), to find out at which redshift (if any) it has been comparable to the present-day late types. The total numbers of intermediate- and of late-type galaxies were scaled to match that of the elliptical galaxies.

been assigned zero mass loss, since they are not FoF-member of their respective cluster⁷ and have never been a FoF-member of a halo with $M \geq 10^{12} M_{\odot}/h$. Negative mass loss values mean that the mass increased since infall. In the top panel of the figure, some late-type galaxies even experienced a complete mass loss, i.e. a value close to 1. In the bottom panel, this is not possible by construction: mass loss serves as the basis for the subdivision itself, therefore late-type galaxies reach only to values of about 0.6. Note that the numbers of intermediate- and late-type galaxies were normalised to that of the elliptical galaxies.

For the present-day elliptical galaxies (black histogram), we show the redshift evolution of the mass loss distribution with the coloured histograms. With increasing redshift, the number of galax-

⁷ We remind that we include in our analysis *all* subhaloes located within 3 Mpc/h of the cluster center, no matter whether or not they are counted as members of the FoF-halo.

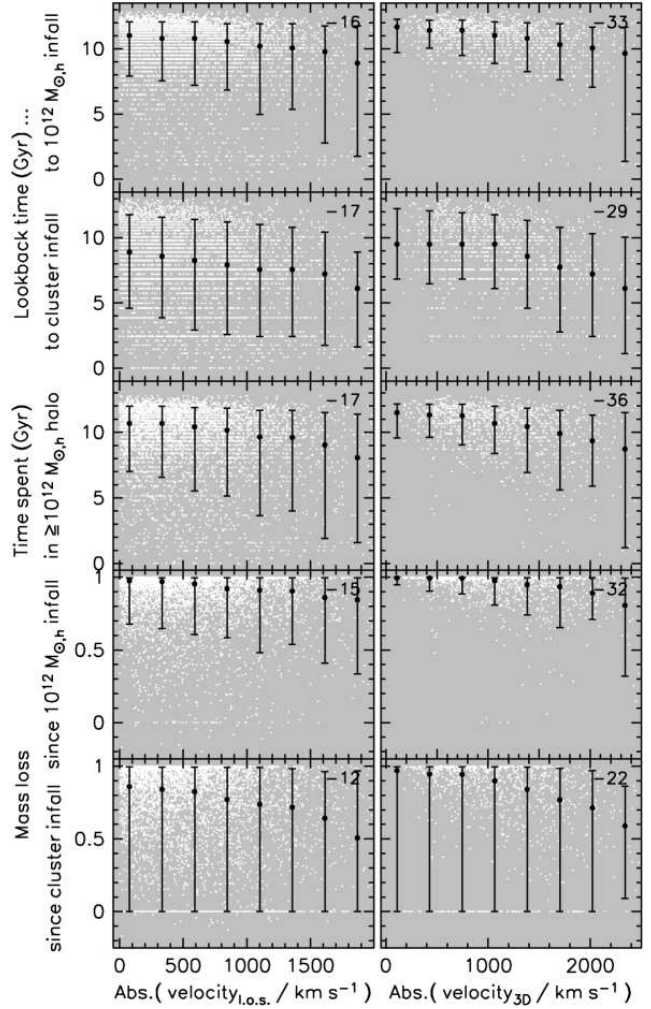


Figure 9. For the dwarf galaxies (white dots) in the 15 most massive clusters of the Millennium-II simulation and located within 0.5 Mpc of the cluster center, we show on the abscissa the absolute line-of-sight velocity relative to the cluster center (left panels, combining all three projections) and the absolute three-dimensional velocity relative to the cluster center (right panels). On the ordinate, we show from top to bottom the lookback time to when a subhalo first entered a halo with $M \geq 10^{12} M_{\odot}/h$, the lookback time to when it entered today's cluster halo, the time spent in haloes with $M \geq 10^{12} M_{\odot}/h$, the subhalo mass loss since it first entered a halo with $M \geq 10^{12} M_{\odot}/h$, and the mass loss since it entered today's cluster halo. Black circles and error bars denote the median and the $\pm 40\%$ range in eight evenly spaced intervals. The black number in the top of each panel is the Spearman's rank correlation coefficient multiplied by 100, calculated within the panel limits. The restriction to a clustercentric distance of less than 0.5 Mpc is applied to the projected distance for the left panels and to the three-dimensional distance for the right panels.

ies that had already experienced strong mass loss is lowered. At the same time, the peak at the value of zero grows higher, indicating that these objects were not yet member of a halo with $M \geq 10^{12} M_{\odot}/h$ at the respective redshift. However, the distribution never looks the same as that of the present-day late types. These have a distribution that decreases at large mass loss values (upper panel of Fig. 8), while the distribution of the ellipticals' progenitors either increases or is nearly flat. If one assumes that only strong subhalo mass loss – e.g. more than 50% – had a noticeable effect on the stellar configuration of the galaxies, then only at red-

shifts between 2 and 3, the ellipticals' progenitors become similar to the late types of today.

4.6 Dependence on velocity

In addition to the clear correlations of projected position with infall time and mass loss, we investigate whether these quantities show an additional correlation with velocity. For this purpose we consider the absolute value of the three-dimensional velocity relative to the central cluster galaxy, as well as the absolute value of the respective line-of-sight velocities along each of the three axes of the simulation box. The line-of-sight velocities do not show any significant correlation with the lookback time to when a subhalo first entered a halo with $M \geq 10^{12} M_\odot/h$, the lookback time to when it entered today's cluster halo, the time spent in haloes with $M \geq 10^{12} M_\odot/h$, the subhalo mass loss since it first entered a halo with $M \geq 10^{12} M_\odot/h$, nor with the mass loss since it entered today's cluster halo.

However, when restricting our analysis to galaxies located within a projected clustercentric distance of 0.5 Mpc, i.e. in the cluster center, weak correlations become apparent (Fig. 9, left panels). While the trends are smaller than the scatter of values, and the individual correlation coefficients are small, the relations give a consistent picture: galaxies moving with larger relative velocities had a somewhat later infall, have spent less time in massive haloes, and have experienced less mass loss. In fact, these correlations are smeared out by projection effects — they are clearly stronger when using three-dimensional quantities (right panels of Fig. 9). This probably reflects the fact that galaxies that entered the gravitational potential of the halo at a later time, when the cluster had already grown to a larger mass, acquired larger velocities until reaching the center.

The comparison between projected and three-dimensional quantities also serves as example for the effect of being in the observer's situation and having only projected quantities available: strong correlations may be somewhat weakened, and weak correlations may become insignificant. We point out that no further or stronger correlations become apparent when using not the absolute values of lookback time and mass loss, but their *residuals* about the relation with projected distance.

Our analysis of subhalo velocities cannot fully explain the observed strong correlation between line-of-sight velocity and shape of nucleated dwarf elliptical galaxies in the Virgo cluster center (Lisker et al. 2009). The finding that those galaxies with lower line-of-sight velocities have significantly rounder shapes had been interpreted such that these have resided in the cluster since a longer time, are therefore on more circularised orbits (see also Biviano & Poggianti 2009) and have suffered more environmental influence. However, while we do find weak correlations of line-of-sight velocity with subhalo mass loss and infall time, these are far from being as clear as the observed correlation with shape, which remains to be understood.

4.7 Dependence on mass

Now we address the question whether the differences between the galaxy populations in the inner and outer cluster regions become more or less pronounced with increasing cluster mass. Fig. 10 compares the lookback time, the time spent in massive haloes, and the mass loss of the inner (white) and outer (black) model galaxy population of each simulated cluster. The inner and outer red galaxy

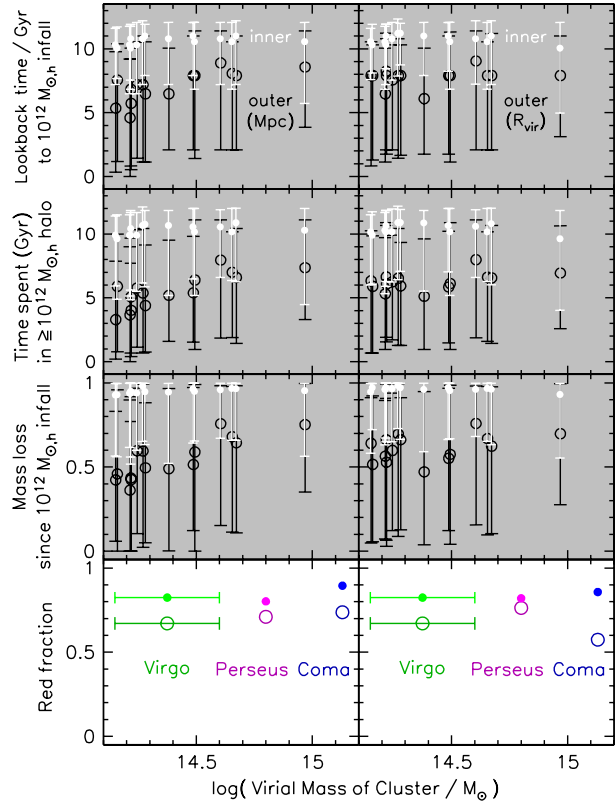


Figure 10. Median and $\pm 40\%$ range of model quantities for the inner (white) and outer (black) subhalo populations of the individual model clusters, shown with respect to cluster mass. The bottom panel shows the red galaxy fractions of the observed clusters. In the left panels, “inner” and “outer” is defined in units of Mpc: less than 0.5 Mpc projected clustercentric distance, and the range 1.0 – 1.5 Mpc, respectively. In the right panels, we define “inner” and “outer” in units of virial radii: less than $0.33 R_{\text{vir}}$ and the range $0.67 - 1.0 R_{\text{vir}}$, respectively. For the Virgo cluster, these definitions are the same, since the virial radius is assumed to be $R_{\text{vir}} = 1.5$ Mpc (McLaughlin 1999). For the Perseus cluster we adopt $R_{\text{vir}} = 1.8$ Mpc (estimated from extrapolating the mass profile of Eyles et al. 1991, see Paper I), and for the Coma cluster we use $R_{\text{vir}} = 2.8$ Mpc (Lokas & Mamon 2003).

fractions of the observed clusters are shown for comparison. Note that the left panels of the figure distinguish between “inner” and “outer” regions in units of Mpc, choosing projected clustercentric distances less than 0.5 Mpc and the range 1.0 – 1.5 Mpc, respectively. In contrast, the right panels are based on units of virial radius R_{vir} , with less than $0.33 R_{\text{vir}}$ for “inner” and the range $0.67 - 1.0 R_{\text{vir}}$ for “outer”, respectively.

The lookback time to when a model galaxy first entered a halo with $M \geq 10^{12} M_\odot/h$ is always high for the inner population. A trend is seen for the outer population, when defined in units of Mpc, that lookback time is increasing with cluster mass (top left panel of Fig. 10). However, this is mostly an effect of choosing absolute units: no significant trend is seen when defining the outer population in units of R_{vir} (top right panel). The situation is the same for the time spent in massive haloes (second row from top), although a slight tendency may be present in units of R_{vir} . When focusing on mass loss (third row from top), again the inner populations are all very similar and have a mass loss close to one. The outer populations, in units of Mpc, show a clear trend of increasing mass loss with cluster mass, and a weak tendency in units of R_{vir} .

The red fractions of observed galaxies show no clear trend for the inner populations. The outer populations follow a slight increase with cluster mass when defined in units of Mpc, and no trend when defined in units of R_{vir} . This may appear similar to the model galaxies, but is of course subject to small number statistics.

In our previous diagrams with clustercentric distance, we have combined the different model clusters and their projections in units of Mpc. Therefore, the differences between inner and outer populations may have been smoothed out a bit, as compared to when we would have used units of R_{vir} . On the other hand, it is not trivial to estimate the virial radius of a cluster from observations, which is why we decided to present our diagrams in units of Mpc instead.

5 DISCUSSION

5.1 Limitations of linking subhaloes with their baryons

Despite the exquisit mass resolution of the Millennium-II simulation, the number of particles that represent a low-mass subhalo is rather small: about 1500 particles for a subhalo with $M = 10^{10} M_{\odot}/h$. Thus, the actual dynamical interaction of tidal field and subhalo, or of two subhaloes, cannot be properly described by a cosmological simulation itself. Moreover, many of the model galaxies in the central cluster regions are orphans, i.e. their subhaloes dropped below the resolution limit of 20 particles and are only tracked by the semi-analytic model. Observations indicate, however, that these objects still hold a significant amount of dark matter (Penny et al. 2009). Therefore, the mass loss, as well as the position and motion of low-mass subhaloes, are merely approximations. Furthermore, dark matter may couple to baryonic processes that change the gravitational potential locally, like gas loss induced by supernovae or by ram pressure. These can affect the dark matter profile and distribution (Governato et al. 2010; Smith et al. 2012a).

Subhalo mass loss begins to occur earlier and already in a less strong tidal field than major changes of the baryonic configuration. This is due to the large extent of the initial halo, which then loses its outer parts and gets truncated when entering a larger potential (Gnedin 2003b; Villalobos et al. 2012). Therefore, when interpreting subhalo mass loss with regard to observable effects, a major fraction of the subhalo can be lost without affecting the baryonic galaxy. This is in line with the majority of late-type analogues having lost $\lesssim 50\%$ of their subhalo mass (Fig. 6): not much harm has yet been done to their stellar disks.

While our study focuses on the mass loss of dark matter subhaloes caused by tidal forces, the strongest ram pressure occurs in the same environments: the highest hot gas densities are found in massive galaxy clusters (Mohr et al. 1999; Helsdon & Ponman 2000). To what extent ram pressure stripping contributes to quenching the star formation activity of galaxies falling into a group or cluster is still a matter of debate (Goto 2005; McCarthy et al. 2008; Book & Benson 2010; Weinmann et al. 2010; Roediger et al. 2011; Bahé et al. 2013; Bösch et al. 2013). It is also noteworthy that there exists a significant scatter in the intragroup medium properties of galaxy groups (Helsdon & Ponman 2000; Osmond & Ponman 2004). Studies aiming to fully simulate the origin of today's dwarf galaxy population thus need to model the variety of environments that affected the galaxies over their lifetime (see Fig. 1).

Simulations and models of environmental processes would also need to account for *spatially resolved* galaxy properties. While having early-type morphology, dwarf galaxies in groups and clusters may still form stars in their inner regions

(Lisker et al. 2006; Tully & Trentham 2008) and contain gas and dust (di Serego Alighieri et al. 2007; De Looze et al. 2010). Even among those not forming stars anymore, the majority of bright early-type dwarfs in the Virgo cluster exhibit a young central stellar population (Paudel et al. 2010a). The blue ultraviolet–optical central colours (Boselli et al. 2008a) of galaxies with overall red colours and old stellar population ages (Roediger et al. 2011) may indicate a recent ram-pressure stripping event (Boselli et al. 2008a) or even the reaccretion of gas (Hallenbeck et al. 2012).

These observations seem to indicate a recent arrival of many early-type dwarf galaxies to the cluster environment, which could mean a discrepancy with the Λ CDM prediction that they are old objects (Boselli et al. 2008a; cf. Figs. 1 and 6). However, it is not straightforward to translate stellar population ages into subhalo histories. When using the ram pressure stripping criterion of Gunn & Gott (1972) as approximation, it can be shown that the Virgo intracluster medium (Vollmer 2009) would *not* be able to remove gas from the centers of most bright early-type dwarf galaxies ($M_r \lesssim -17$ mag).⁸ Only for fainter galaxies should its ram pressure seriously affect *all* parts of the galaxy, thus predicting that the Next Generation Virgo Cluster Survey (Ferrarese et al. 2012) will not find faint early-type dwarfs with blue central regions.

The above considerations emphasize the complexity of the real situation, involving gas, stars, their time evolution, and their dependence on local conditions. The subhalo distributions and histories that we analysed constitute the underlying cosmological framework — not more and not less.

A further caveat lies in the applicability of current semi-analytic models of galaxy formation in cosmological volumes, which are still facing difficulties in reproducing the properties of low mass galaxies. For example, they predict too little late evolution in their number density (Weinmann et al. 2012), too red colours in galaxy groups (Paper I), as well as stellar metallicity and age distributions that do not agree with observations (Pasquali et al. 2010). These aspects are one reason why we primarily rely on dark matter subhalo distributions for our analysis, instead of using the “observables” provided by the semi-analytic model for our comparison with observations.

5.2 Correlations with clustercentric distance

The anticorrelations of mass loss and lookback time to infall with clustercentric distance (e.g. Fig. 4; Smith et al. 2012d) seem to provide a natural explanation for the observed morphology-distance relation (Binggeli et al. 1987). Spending a longer time inside massive haloes means to experience stronger tidal forces and presumably also stronger interaction with the intracluster medium, leading to an earlier and more efficient transformation of the morphological properties and quenching of the star formation activity (Smith et al. 2008, 2012d).

Early-type dwarf galaxies also show a morphology-distance relation of their own subtypes (Lisker et al. 2007), as well as

⁸ At a clustercentric distance of 0.5 Mpc, the density of the Virgo intracluster medium as modeled by Vollmer (2009) provides a ram pressure of $10^{-11.8} \text{ Nm}^{-2}$. We select Virgo early-type dwarf galaxies with $M_r < -17$ mag and projected axis ratio above 0.85, and use *ugriz*-photometry to approximate their stellar surface mass density (based on Hansson et al. 2012) at one exponential scale length. When assuming a gas surface density of one tenth of the stellar surface density and a relative velocity of 1000 km/s, we obtain estimates for the restoring force per unit area between $10^{-12.2}$ and $10^{-10.0} \text{ Nm}^{-2}$.

a dependency of the colour-magnitude relation on local density (Lisker et al. 2008). Those early-type dwarfs with signatures of disks and/or without a bright stellar nucleus are preferentially found outside of the cluster core. These also exhibit younger ages of their stellar populations, deduced from stronger Balmer absorption lines (Paudel et al. 2010a for the Virgo cluster), from narrowband Strömgren photometry (Rakos & Schombert 2004 for the Coma and Fornax clusters), and from ultraviolet–optical colours (Kim et al. 2010 for Virgo). Accordingly, Smith et al. (2008) found that red-sequence dwarf galaxies in the Coma cluster outskirts show stronger Balmer lines than those in the center. This can be understood in the light of our analysis: even within a given subpopulation, a radial trend exists for mass loss and for the time spent in massive haloes⁹ (Fig. 6; cf. Smith et al. 2006 and von der Linden et al. 2010 for bright galaxies).

On the other hand, the various structural subgroups of Virgo early-type dwarfs that were identified in the comprehensive near-infrared study of Janz et al. (2013) do not exhibit clear trends with respect to clustercentric distance. Ryś et al. (2012) point out that the individual histories of the galaxies *should* lead to a significant spread in their characteristics at a given distance from the cluster center. This is in line with the substantial scatter in subhalo mass loss and time spent in massive haloes when considering the combined population of dwarf elliptical analogues and intermediate types (Fig. 6).

After it had become clear that a major fraction of early-type dwarf galaxies exhibit significant rotational velocities (Simien & Prugniel 2002; Chilingarian 2009), Toloba et al. (2009) reported a tendency for them to show increasing rotational support with increasing distance from the Virgo cluster center. While this would seem complementary to the above trends of morphology and stellar populations, the kinematical diversity of early-type dwarf galaxies is large (Ryś et al. 2012) and published samples are still incomplete. Again, a significant scatter is expected from our analysis, since clustercentric distance cannot be directly translated into the specific history of a subhalo.

Those early-type dwarf galaxies that reside in cluster cores have experienced high-density environments already at early epochs (Fig. 8). For them, more intense early star formation could have caused the larger fraction of stellar mass in the form of globular clusters (Moore et al. 2006; Peng et al. 2008) as compared to galaxies in today’s cluster outskirts or even the field (Sánchez-Janssen & Aguerri 2012). Interestingly, the fraction of early-type dwarfs with bright stellar nuclei that exceed typical globular cluster luminosities (Côté et al. 2006) is also much larger in the cluster center (Ferguson & Sandage 1989; Lisker et al. 2007). We can thus speculate that the efficient early formation of globular clusters (and possibly ultra-compact dwarf galaxies, Mieske et al. 2012) in those regions was paralleled by an efficient formation of such stellar nuclei. This shows that, on top of the subhalo distribution and evolution, it is necessary to take into account the environmental and time dependence of baryonic processes to obtain a consistent picture of the formation of today’s dwarf galaxies.

5.3 The dwarf galaxy population in a Λ CDM universe

From their analysis of the dwarf galaxy population in nearby clusters, Sánchez-Janssen et al. (2008) concluded that the red dwarfs in the central cluster regions could be related to the population of blue dwarf galaxies observed in high-redshift clusters. However, at the brighter dwarf magnitudes, the red sequence was even reported to be established and well populated in clusters up to redshift $z \leq 1.3$ (Andreon 2006, 2008). Many of the red-sequence galaxies in cluster cores experienced environmental effects already at high redshifts (Figs. 7 & 8) and entered the cluster halo very early (De Lucia et al. 2012b; Smith et al. 2012d).

On the other hand, clusters grow by accretion of field and group galaxies (cf. Adami et al. 2005). Out of the 7673 model dwarf galaxies that are FoF members of the 15 most massive Millennium-II clusters at redshift zero, two thirds (66.9%) joined their present-day cluster halo at redshifts $z < 1$, and still more than one third (36.4%) joined at redshifts $z < 0.5$ (see also Smith et al. 2009). The majority of galaxies (57.2%) were accreted as satellites of a group or cluster (also see McGee et al. 2009, De Lucia et al. 2012b, and Smith et al. 2012d). Environmental effects on galaxies in groups before cluster accretion – so-called pre-processing – are therefore expected to be of high relevance, as was noted also by De Lucia et al. (2012b). Villalobos et al. (2012) showed from simulations that stellar disks can indeed be significantly affected (thickened, heated, shrunk) by a group tidal field after several gigayears (also see Mayer et al. 2001), once the bound dark matter fraction drops below $\sim 30\%$ of its initial value. Even when only few percent of the stellar mass are lost, significant disk thickening ($>50\%$) can occur for galaxies with low mass and/or high orbital eccentricities.

McGee et al. (2011) found that groups do not only contain a larger fraction of passive galaxies than the field, but that this fraction is larger for galaxies of lower mass and has grown over time, supporting the notion of continuous environmental influence on dwarf galaxies in groups.¹⁰ Furthermore, evidence for the relevance of the large-scale environment is given by the findings of Lietzen et al. (2012) that groups of equal richness have a higher fraction of elliptical galaxies when they reside in supercluster environments. Therefore, the fact that massive galaxy clusters contain, on average, a larger fraction of dwarf elliptical galaxies than groups (e.g. Tully & Trentham 2008) should not only be ascribed to stronger environmental effects *inside* the cluster (also see Bahé et al. 2013). Instead, the galaxy content of accreted groups had probably evolved further than that of groups in lower-density environments, which survived until today.

When using our analysis of subhalo histories to interpret galaxy populations, we also need to consider that the baryonic structure at early epochs was different than in late-type galaxies today. At $z > 2$, when part of the progenitors of today’s dwarf ellipticals already experienced strong mass loss of their subhaloes (Fig. 8), the disk component may not yet have had completed its formation (Governato et al. 2010). At redshifts $z \gtrsim 1$, many star-forming galaxies had a clumpy appearance (Elmegreen et al. 2004) and likely represented an early phase of the spiral galaxy formation process (Bournaud et al. 2007; Elmegreen et al. 2009). These aspects would also be relevant for simulations of early interactions of gas-rich galaxies that yield tidal dwarf galaxies (Dabringhausen & Kroupa 2013), which may

⁹ We note that this trend arises as a direct consequence of mapping mass loss to morphological type, since the anticorrelation of mass loss with clustercentric distance is stronger than with morphological type.

¹⁰ We note that, for galaxies with luminosities equal or larger than $0.3L_*$, Berrier et al. (2009) concluded that pre-processing is of minor importance.

constitute a relevant part of the observed dwarf galaxy population (Kroupa 2012). After their stellar structure had developed, dwarf galaxies rarely experienced a major merger (De Lucia et al. 2012a). Of the model galaxies in our SAM-V sample, only 3.1% have experienced at least one major merger since $z = 1$ (5.3% since $z = 2$).¹¹ Major mergers thus only had a small contribution to the structural appearance of dwarf galaxies in clusters today.

Resulting from the interplay of various processes integrated over cosmic time, the present-day galaxy populations can be described by the classification scheme of van den Bergh (1976) and Kormendy & Bender (2012). This scheme groups lenticular and early-type dwarf galaxies into a parallel sequence to spiral and irregular galaxies. Given our analysis and the above considerations, today’s early-type dwarf galaxies have not only experienced stronger subhalo mass loss than today’s late-type galaxies of the same cluster, but have also resided in different environments for a large part of their lifetime. Therefore, the two parallel classification sequences do not mean that the progenitor of a *present-day* early-type galaxy looked like a *present-day* late-type galaxy. Instead, the early-type sequence is most likely a consequence of stronger halo clustering and stronger influence of various environments over many gigayears — described as “history bias” by De Lucia et al. (2012b). The progenitors of the late-type sequence probably formed under different conditions, evolved at a different pace, and remained largely undisturbed by external influence. Late-type galaxies that are currently falling into massive clusters may thus not be good representations of the real progenitors of dwarf elliptical galaxies.

6 CONCLUSIONS

We investigated the history of the present-day dwarf galaxy population in clusters from the perspective of the Millennium-II Λ CDM cosmological simulation and the Guo et al. (2011) semi-analytic galaxy model. In cases where a dark matter subhalo in the simulation did not lose a substantial amount of its mass over time, we can assume that the stars and gas were not affected noticeably by tidal forces, and consequently we identify these cases with late-type galaxies. Only in cases with strong subhalo mass loss can we assume that the baryonic configuration of the galaxy has also been affected significantly. These cases are identified with elliptical galaxies, subsuming dwarf ellipticals and low-luminosity ellipticals. Assigning galaxy types to subhalo populations in this way leads to a morphology-distance relation very similar to what is observed in the Virgo and Coma clusters.

We find that the median subhalo mass loss decreases more steeply with clustercentric distance than the observed elliptical fraction, and therefore also steeper than the increase of the late-type fraction. This can be resolved when assuming that ellipticals in the cluster core experienced even stronger environmental effects than ellipticals in the outskirts; the same applies to the intermediate-type and late-type galaxies. However, the properties of different model clusters and their projections show significant scatter, which could alleviate the differences.

¹¹ When subdividing them into early, intermediate and late types by the time spent in massive haloes, as in Fig. 5, the fractions are 0.5% (2.1%) for early types, 2.4% (5.8%) for intermediate types, and 5.9% (8.2%) for late types. These numbers increase only mildly when restricting our sample to the brightest dwarfs ($-19.0 < M_r < -18.0$ mag).

The above statements also hold when using the time that subhaloes have spent in massive clusters, instead of their mass loss. Similar conclusions have been drawn based on infall time into a massive halo (De Lucia et al. 2012b; Smith et al. 2012d). While we argue that subhalo mass loss is more directly related to the tidal influence on the baryonic galaxy, we also note that the cosmological simulation is limited in its particle resolution of subhaloes, and can therefore only provide approximate values.

Our study shows that the majority of present-day dwarf ellipticals have already experienced strong mass loss of their subhaloes at high redshifts ($z > 1$). They have accordingly spent most of their lifetime in massive haloes ($M \geq 10^{12} M_\odot/h$). This emphasizes the importance of environmental effects that acted in galaxy groups and “pre-processed” the galaxies before they entered the cluster. Dwarf ellipticals were thus not formed recently, but are likely a product of early and continuous environmental influence. We argue that this does not contradict small fractions of young stellar populations in these galaxies. The central gravitational potential of the brighter early-type dwarfs is sufficiently deep to shield gas from being stripped.

Over their lifetime, present-day late-type galaxies have experienced an amount of environmental influence that is comparable to what the progenitors of dwarf elliptical galaxies had already experienced at redshifts $z > 2$. In fact, there is no redshift at which the distributions of subhalo mass loss of today’s late types and high-redshift progenitors of dwarf ellipticals agree. This reflects the fact that they evolved in different local *and* large-scale environments. Simulations aiming at reproducing the formation of dwarf elliptical galaxies would therefore need to take into account the environmental characteristics of (proto-)clusters and groups at high redshift, as well as the fact that the progenitor galaxies themselves were at a much earlier stage of their evolution.

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